The Carbon Balance Observatory (CARBO) Instrument for Space-based Observation of Greenhouse Gases

Shannon Kian Zareh, Charles E. Miller, J. Kent Wallace, Peter Sullivan, Andre Wong

Jet Propulsion Laboratory, California Institute of Technology

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Overview of Presentation

- Programmatic Overview
- CARBO concept Science Overview
- Instrument Architecture
- Key Technologies
  - Immersion Gratings
  - Focal Plane Array
  - Polarization Sensing
- Instrument Radiometric Performance Estimate

Programmatic Overview

- Funded by Instrument Incubator Program (IIP)
  - NASA's Earth Science Technology Office (ESTO)
- Institutions:
  - Jet Propulsion Laboratory
  - University of Texas at Austin
  - Caltech
- Goal:
  - Develop new suite of instruments to measure atmospheric gases that are more capable.
  - Advance immersion gratings and modular instrument architecture.

CARBO Concept

Science Goals

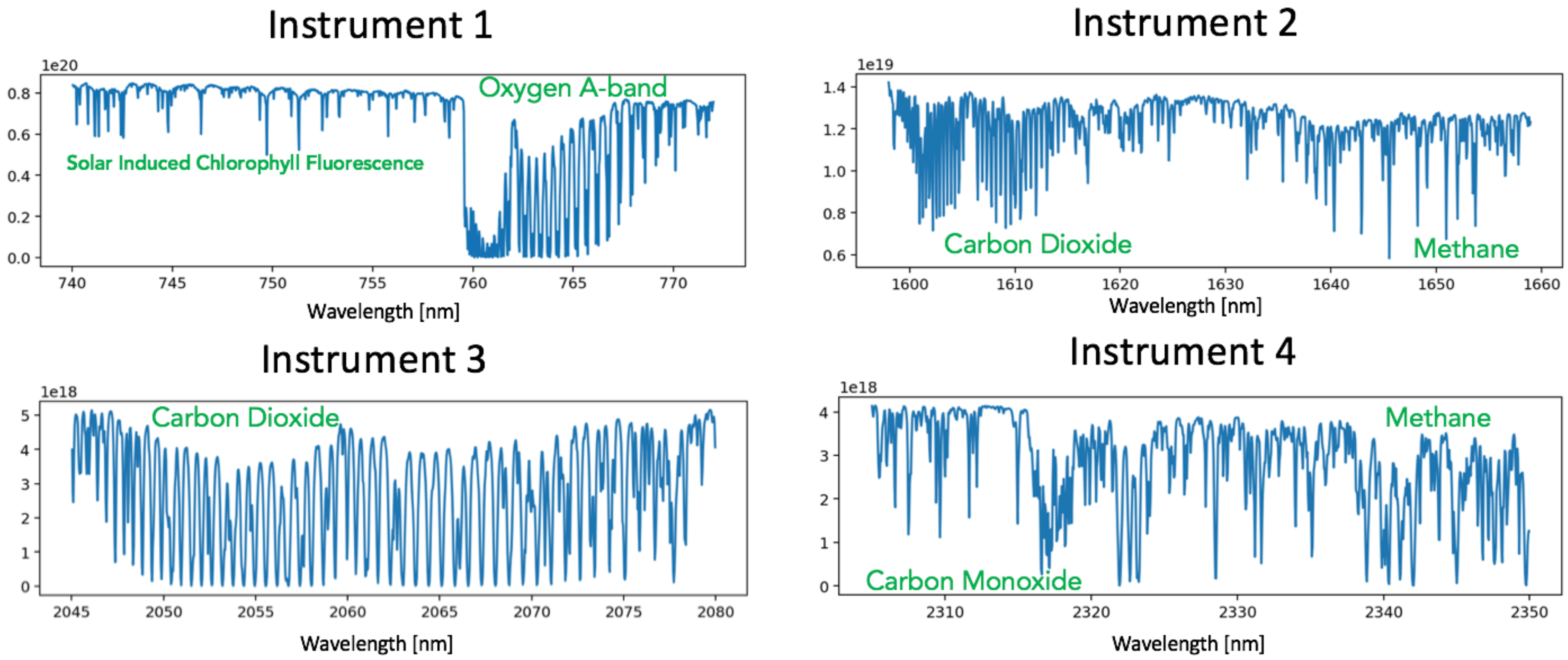
- Measure column-average dry air mole fraction (X) of CO2, CO, CH4 and SIF.
  - XCO2: 1.5 ppm
  - XC0: 5 ppb
  - XCH4: 7 ppb
  - SIF: < 10% error
- Spatial and temporal coverage
  - Spatial sampling of 2 km x 2 km on the ground from LEO
  - Instantaneous FOV: 5 - 15 degrees
  - Full coverage, once a week
  - 5-20 times greater spatial coverage than OCO-2

CARBO Science Goals

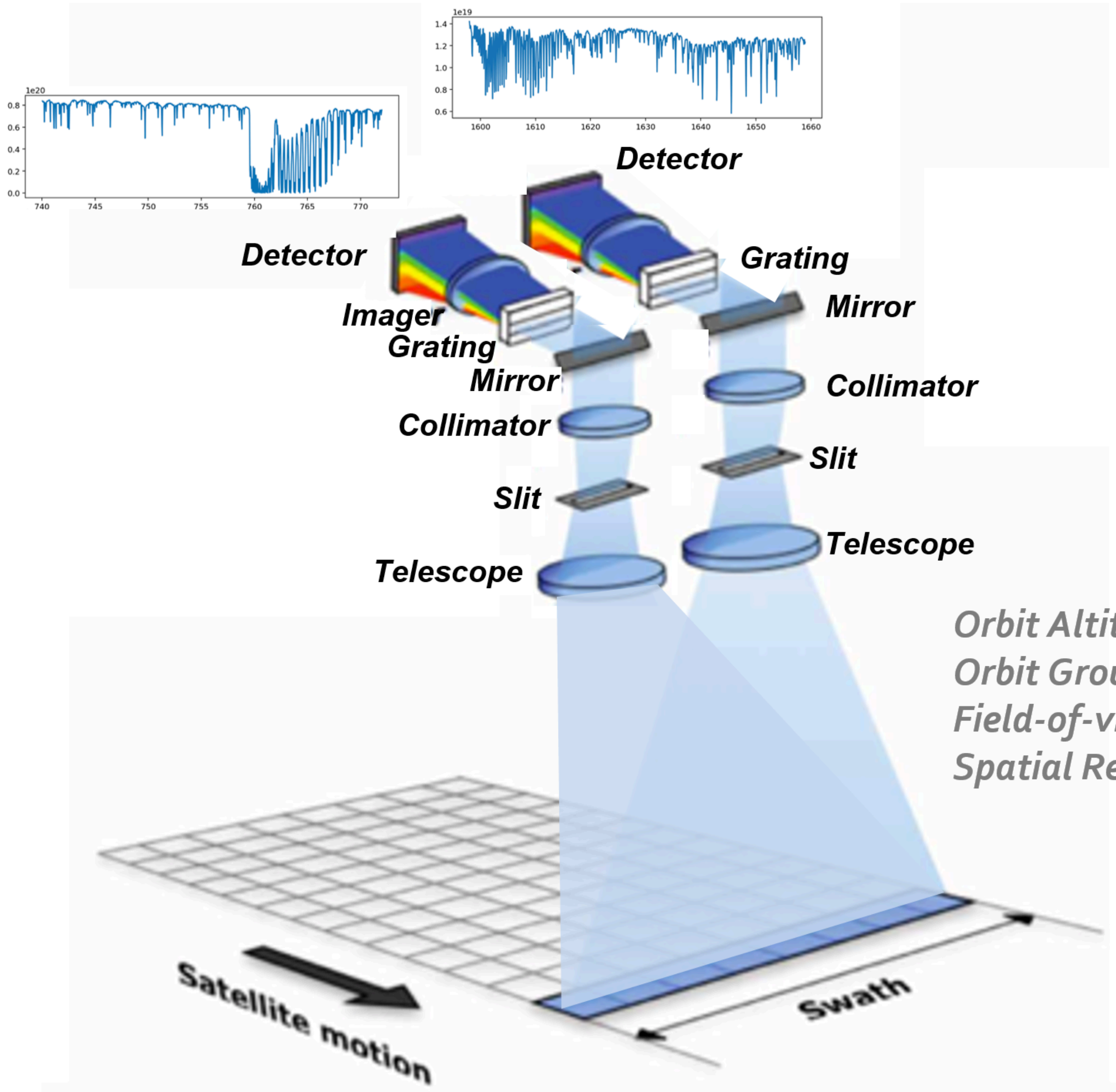
CARBO Requirements	Design, Build, Field Test		Design	
	Instrument 1	Instrument 2	Instrument 3	Instrument 4
Spectral Range (nm)	745 - 772	1598 - 1659	2045 - 2080	2305 - 2350
Measurement Targets	O_2, SIF	CO_2, CH_4	CO_2	CO_2, CH_4, H_2O
SNR @ 5% albedo and 65^O SZA	> 300	> 350	> 150	>100
Spectral resolution FWHM (nm) at λ_{ave}	0.05	0.15	0.10	0.12
Spectral Resolving power at λ_{max}	15,440	11,060	20,800	19,583
Retrieval Precision	X_{CO2}<1.5 ppm, X_{CH4}<7 ppb, X_{CO}<5 ppb, SIF <20%			

SIF – Solar Induced Chlorophyll Fluorescence

CARBO Science Overview



Instrument Architecture



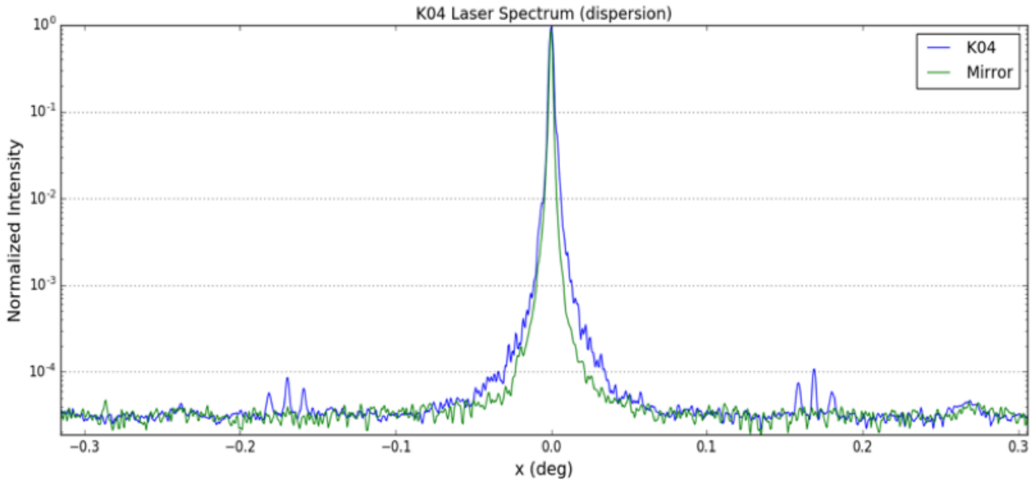
Orbit Altitude:	*705 km*
Orbit Ground Velocity:	*6.767 km/sec*
Field-of-view:	*6 degrees*
Spatial Resolution:	*2 km x 2 km*

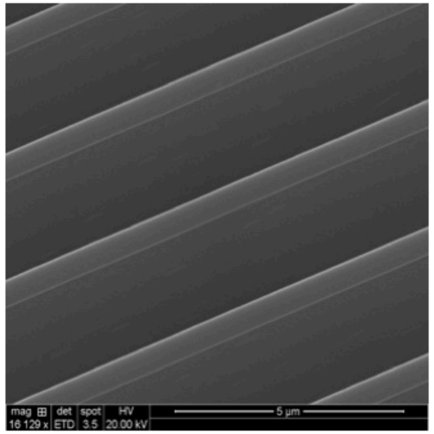
Key Technologies: Immersion Gratings

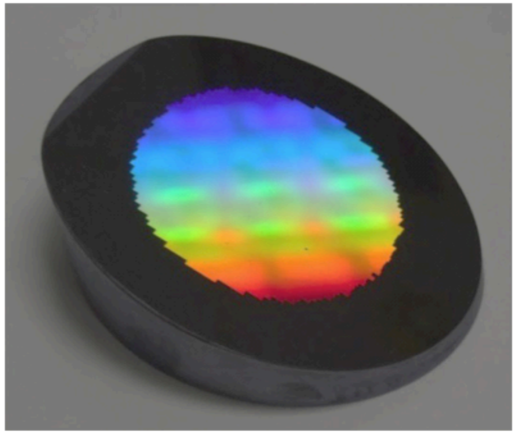
- Immersion gratings reduce the size and mass of echelle gratings without sacrificing performance.
  - Diffraction occurs internal to the material.
  - Grating scales as index of refraction.
  - In silicon, grating facets are made via anisotropic etching resulting in atomic level features.
  - Scattering due to imperfections is minimized.

Cindy Brooks
Univ Texas

Dan Jaffe
Univ Texas



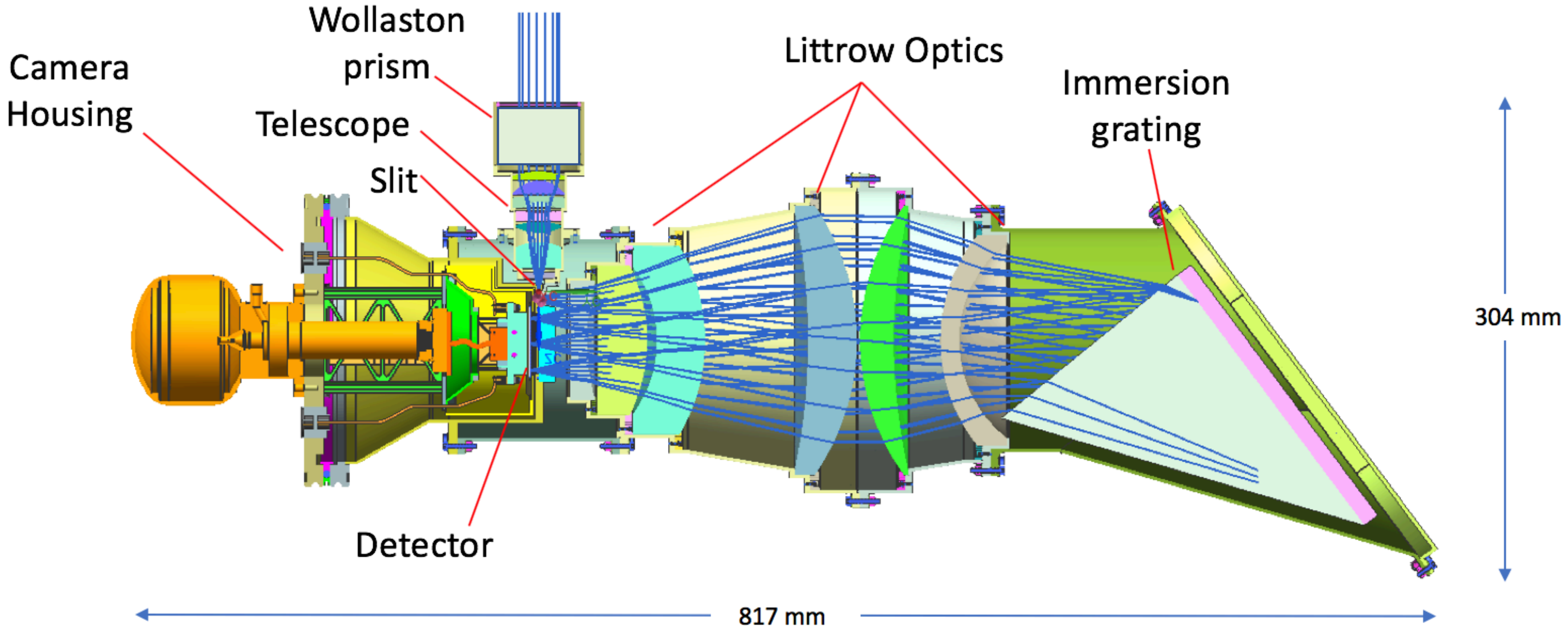




ACT Si Immersion Grating

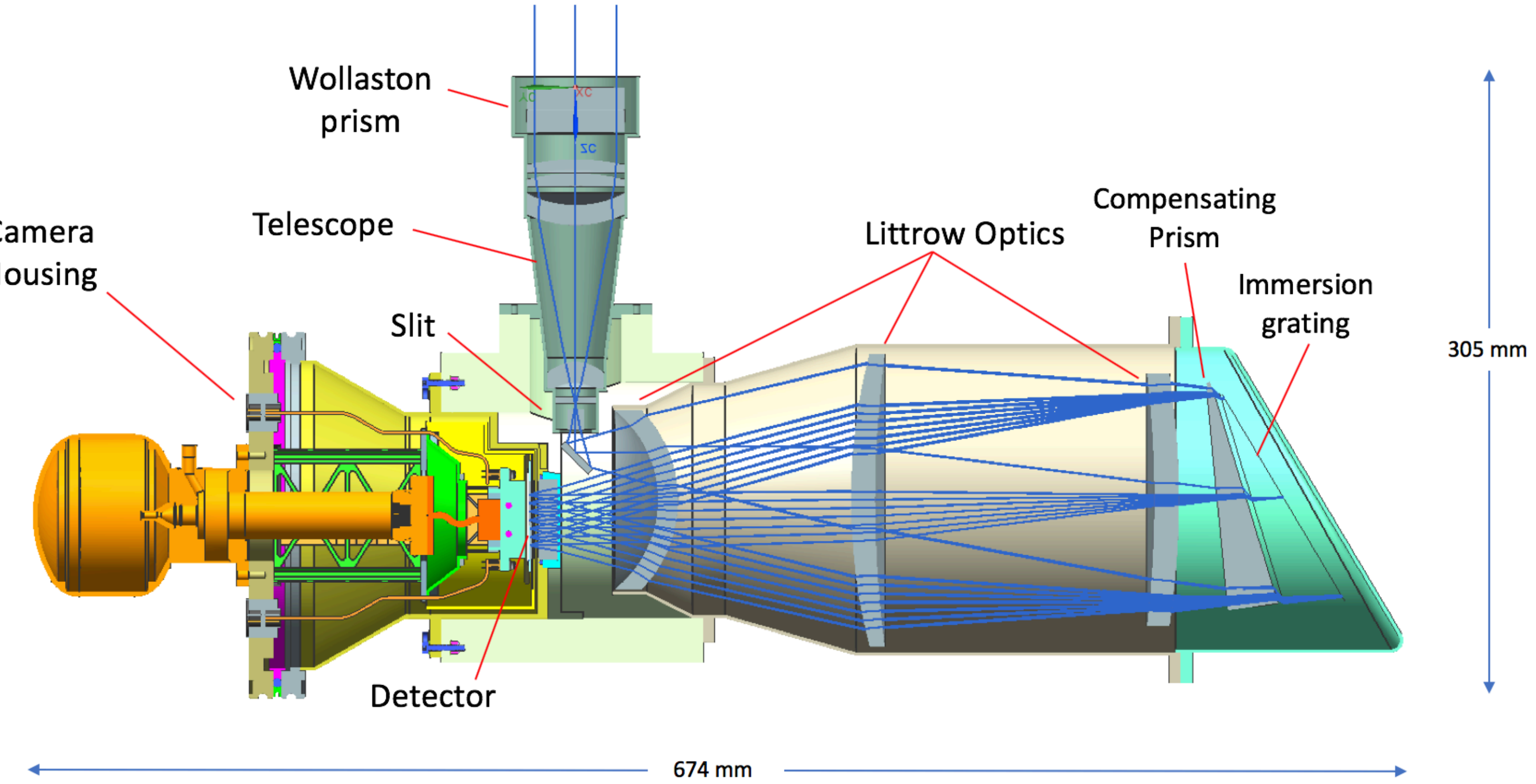
Instrument 1: Conceptual Opto-Mechanical Layout

Instrument 1
(745 – 772 nm for Oxygen-A band and SIF remote sensing)

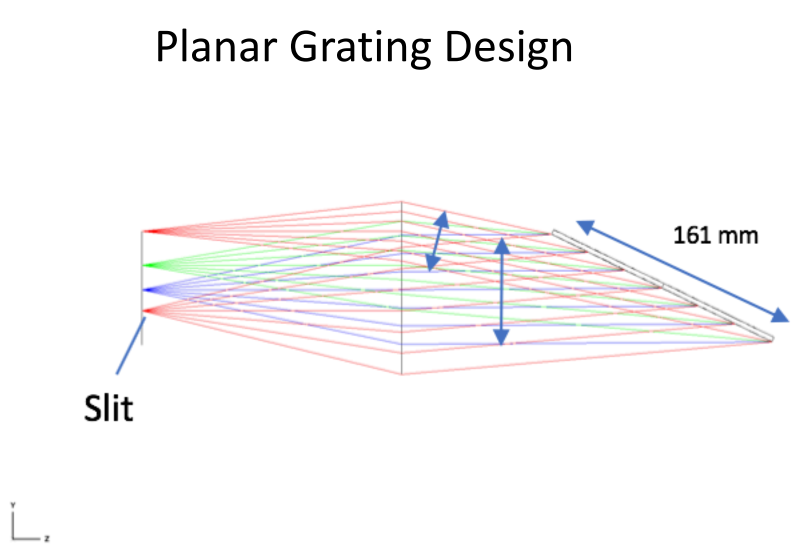


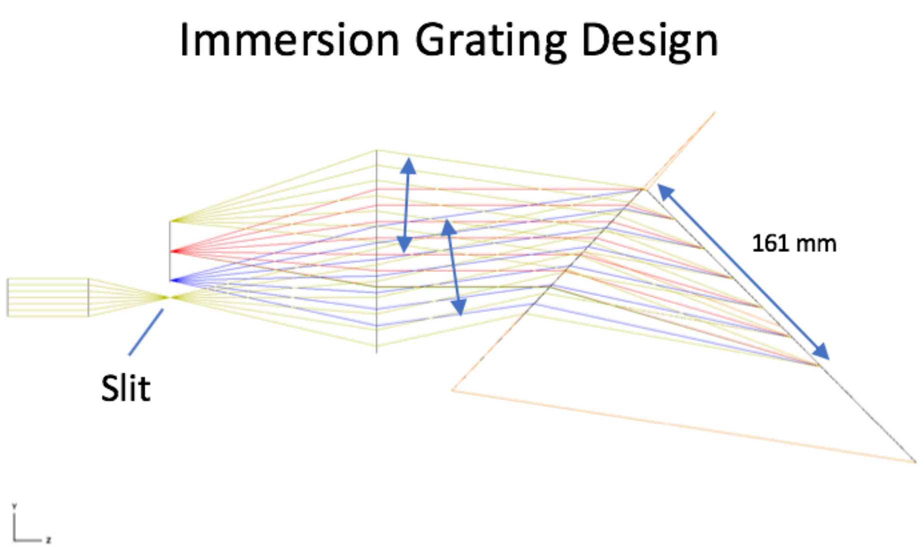
Conceptual Opto-Mechanical Layout

Instrument 2
(1595 – 1659 nm for CO_2 and CH_4 remote sensing)



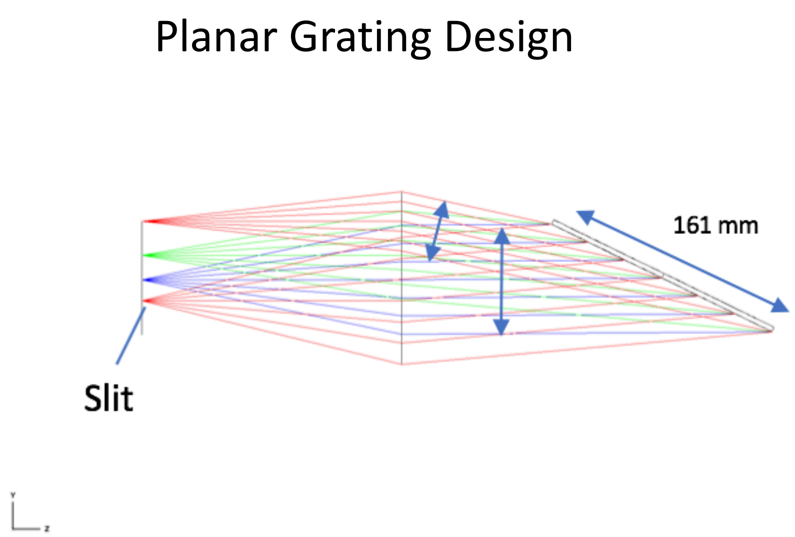
Immersion Grating vs. Planar Echelle Grating

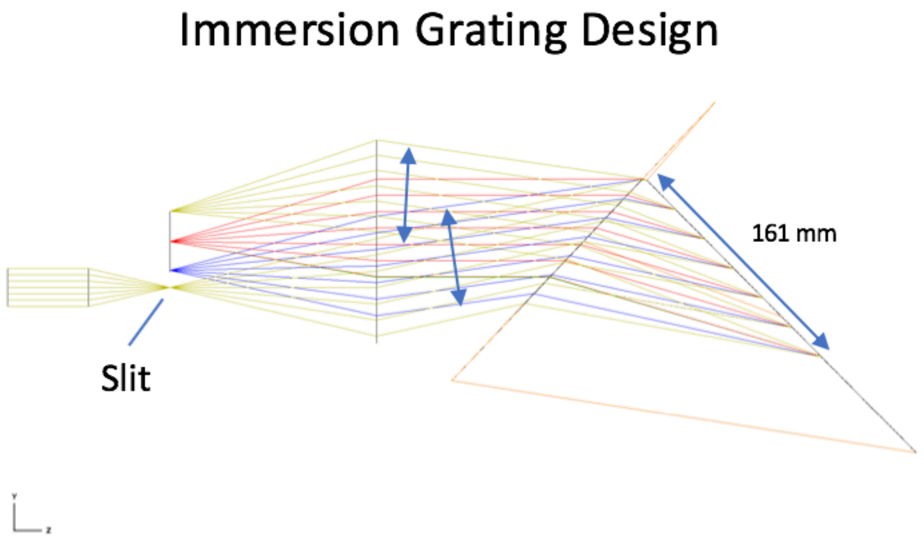




- Both designs are optimized for the same diffraction grating length (161 mm), and the same dispersion
- For plane grating, anamorphic beam compression is much greater factor than for immersion grating design
- With traditional air grating the spectral resolving power varies by a factor of 1.8 over the band. With compensation, however, this can be reduced to a variation of 1.08 – an order of magnitude improvement.

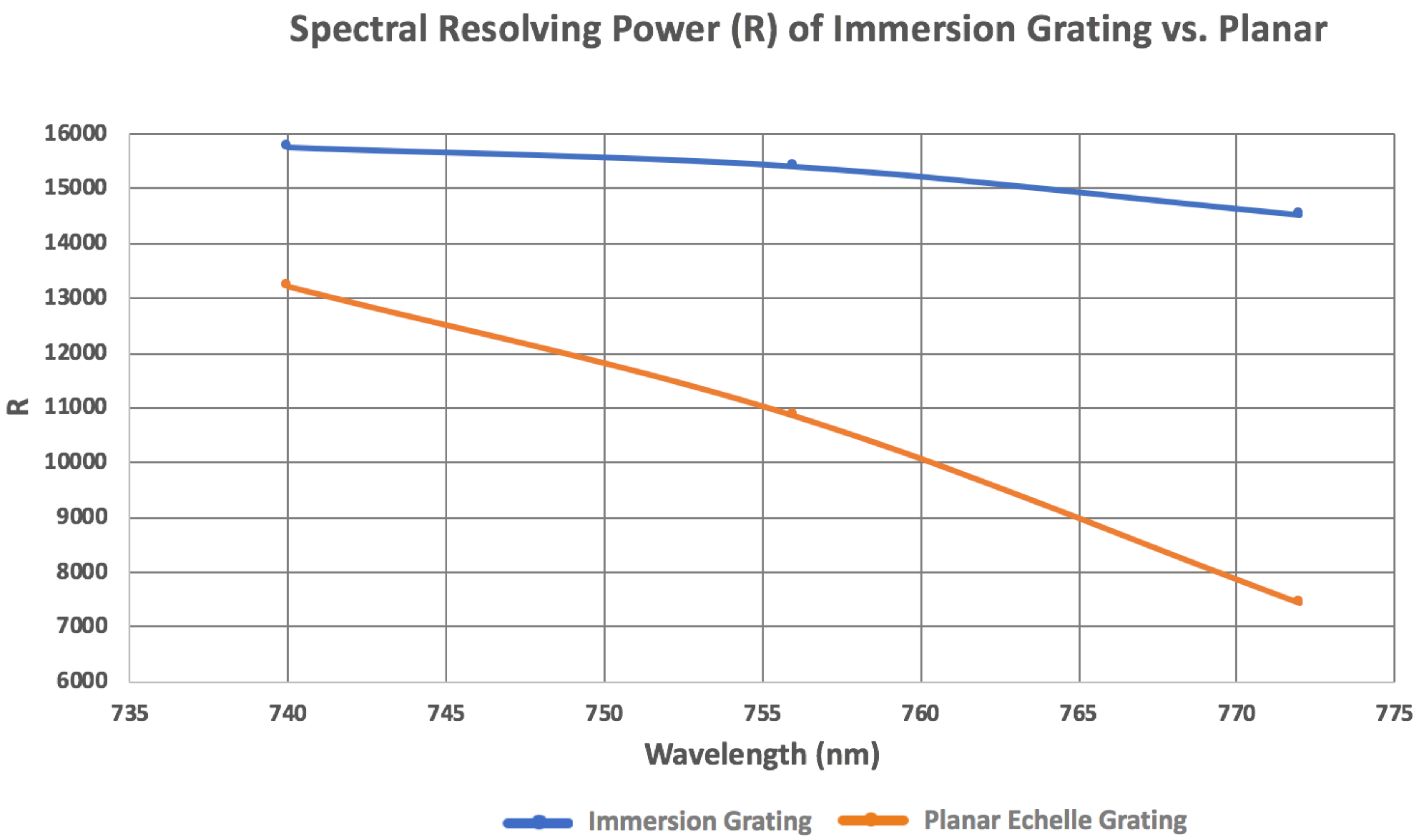
Immersion Grating vs. Planar Echelle Grating





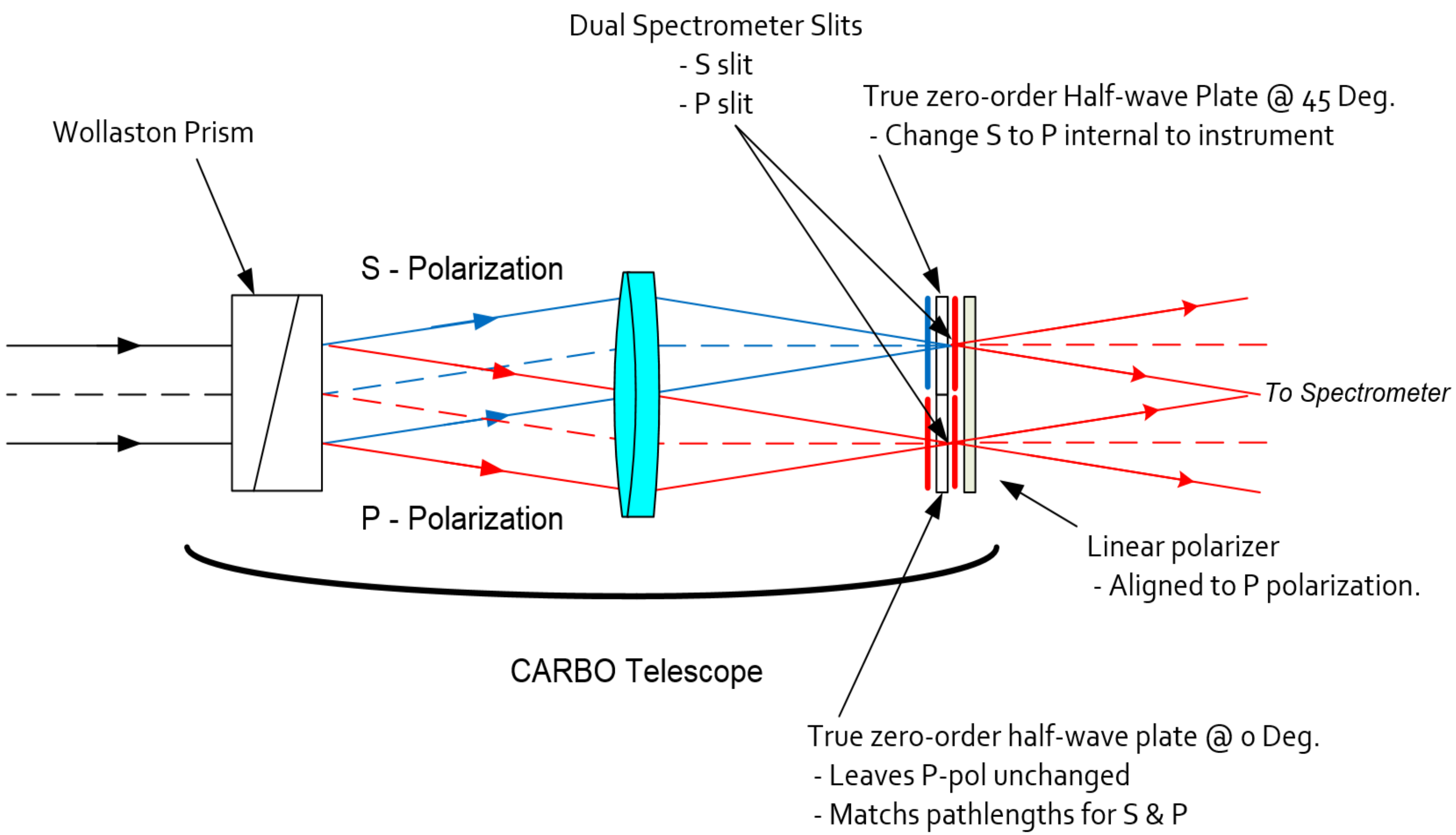
- Anamorphic compression results in an asymmetric point-spread function (PSF) in the final image plane
  - Anamorphic remapping of the pupil can be largely compensated by the action of a compensating prism – either integral to the immersion grating itself or a separate element used in conjugation with the immersion grating
  - The result of anamorphic correction is that the spectral resolving power is much more uniform, because the PSF is more uniformly symmetric over wavelength and therefore properly sampled by the detector in a more uniform way

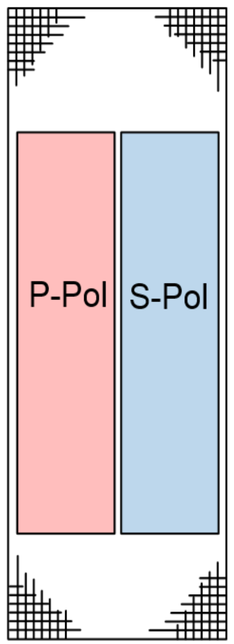
Spectral Resolving Power



- At the same grating length of 161 mm, the spectral resolving power for plane grating design is significantly lower than for immersed grating design
- Plane grating design show greater variation of resolving power across spectral band

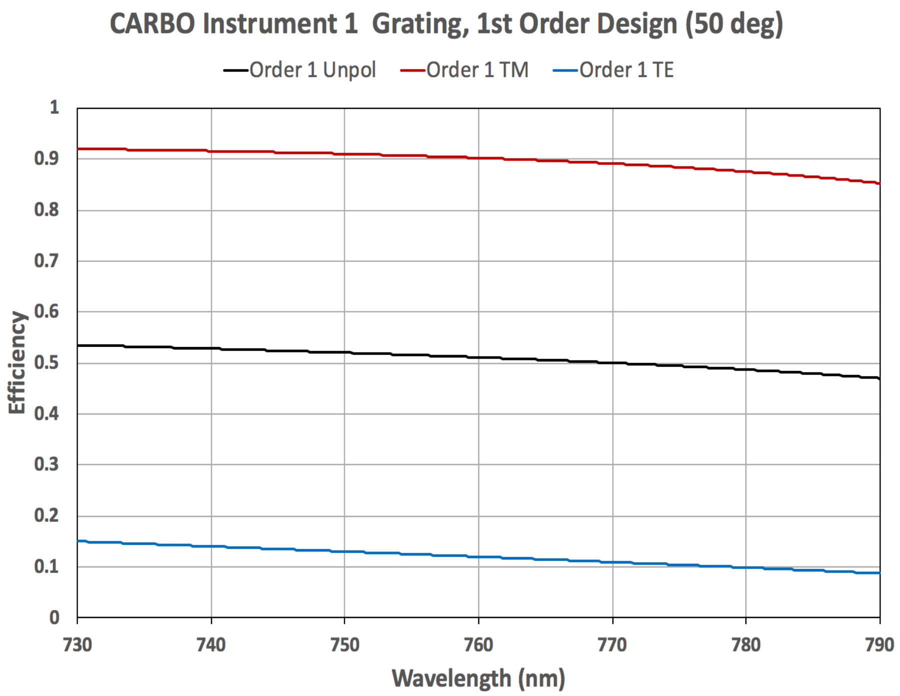
Key Technologies: Polarization Sensing

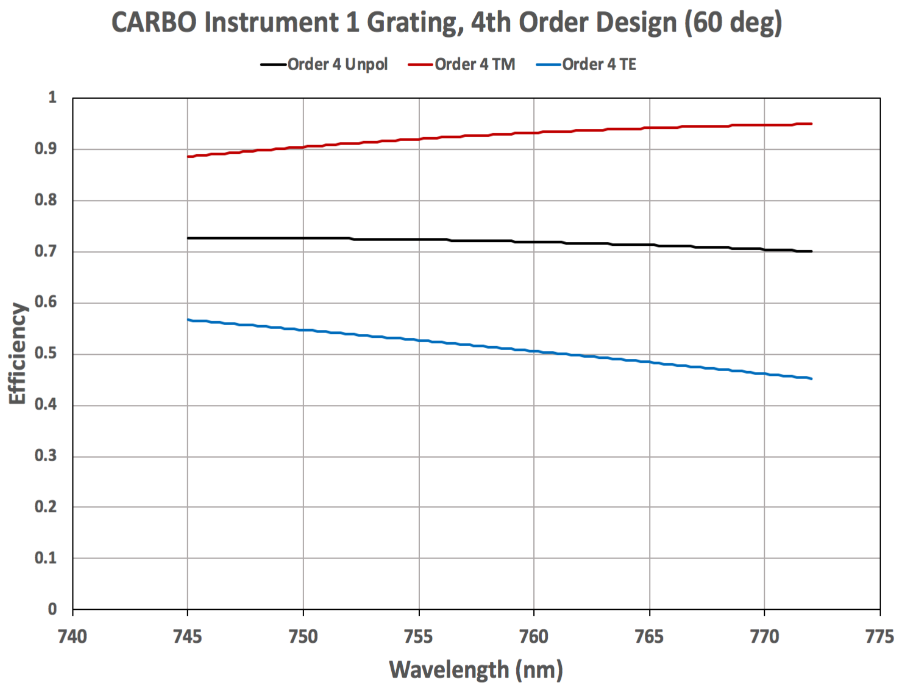




Both Polarization states on the detector simultaneously

Polarization Dependent Efficiency





Key Technologies: Polarization Sensing

- Advantages of Simultaneous Dual Polarization Sensing:
  - Engineering Perspective:
    - Increase grating efficiency,
    - Perfectly matches the polarization efficiency,
    - Simplifies immersion grating fabrication.
    - Shortens the fabrication schedule.
  - Science Perspective:
    - Improves degrees of freedom for all species
    - Enhances sensitivity to surface BRDF, including surface polarization effects
    - Improves sensitivity to aerosol composition (better constraints on scattering parameters) and better discrimination of atmospheric and surface scattering
    - Enables superior discrimination of vertical distribution of gases and aerosols
      - CO_2, CH_4, CO and aerosol profiles

Key Technologies: CHROMA-D

- CARBO design incorporates the latest infrared focal plane technologies from Teledyne Imaging Sensors (TIS)
- The CHROMA-D focal plane adds on-chip digitization; without the need for complex analog-to-digital electronics supporting the FPA, the CHROMA-D allows a simpler overall design for the CARBO instrument.
- The CHROMA-D FPA consists of an 18um pixel pitch HgCdTe detector hybridized to a CHROMA-D digital ROIC

Detector Parameter	TIS 2.5um HgCdTe Performance
QE	
- 800nm	≥70% (≥80% goal)
- 1000nm	≥70% (≥80% goal)
- 1230nm	≥70% (≥80% goal)
- 2000nm	≥70% (≥80% goal)
Median Dark Current (140K)	100 e-/s/pix
Operability	≥95% (≥99% goal)

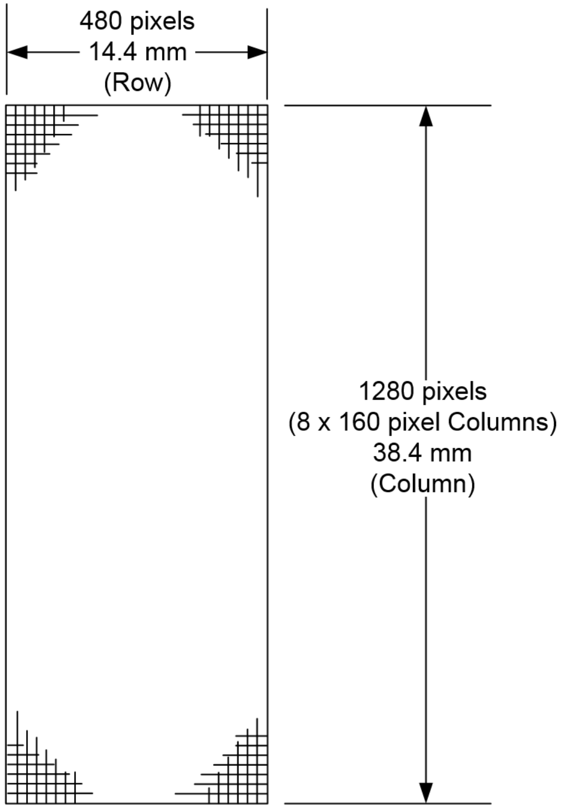
Typical Performance for TIS 2.5um-cutoff HgCdTe detectors

ROIC Version		High Gain	Low Gain
A0	Full Well (e-)	100,000	1,000,000
	Readout Noise (e- RMS)	25	150
A1	Full Well (e-)	180,000	2,700,000
	Readout Noise (e- RMS)	35	300

Predicted full well and readout noise performance for the 2 different version of the CHROMA-D ROIC

Key Technologies: Detector Technology

CHROMA-A Detector Data Sheet
CARBO Channel 1



Detector Properties

Vendor	Teledyne
Name	CHROMA - A
Pixel Size	30 um x 30 um (H x V)
Array Size - pixels	1280 x 480 (H x V)
Array Size - mm	38.4 mm x 14.4 mm
ROIC Size - mm	43.2 mm x 19.4 mm
Detector Material	HgCdTe
Wavelength Range	~ 0.330 – 2.50 um
Well Depth	1.0 M e-
Read Noise (CDS)	110 e-, RMS
Dark Current	0.8 M e-/sec/pixel (@ 180K)
Frame Rate	125 Hz, Full Frame/250 Hz Half Frame
No. of Outputs	8 (1 Output per 160 Columns)
Readout Mode	Snapshot
Row Readout	16.8 um sec
Port Readout Rate	10 Mpixels/sec
Power (FPA)	300 mW

FPA Noise Assumptions for Performance Estimate

	CHROMA-A		CHROMA-D (A_0 series)	CHROMA-D (A_1 series)
Charge Capacity (k e-)	700	1000	1000	180
Pixel pitch (m)	30		18	
Dark Current (e-/pix/s)	1440		100	
Dark Noise (e-/pix)	14		4	
Read Noise (e- rms)	80	129	150	35
Electronics Noise (e- rms)	50	70	N/A	N/A
Quantization Noise (e- rms)	10.7	15.3	61	11

The noise values used for CHROMA-A are for an engineering-grade FPA, and the noise values for CHROMA-D are based on theoretical projected values. Additionally, the electronics noise for the CHROMA-A FPAs is based on the JPL-designed CHROMA-A electronics described in Section 2.2.3. *Dark Current values estimated at the CARBO operating temperature using “Rule07” with a 100x derating factor

Instrument Performance and FPA Array Size

	Instrument 1			
	Current design			Future (flight) design
FPA	baseline FPA (CHROMA_A)	Baseline design, integrated with 18 micron pixel FPA	Baseline Design, Integrated with small format CHROMA-D	large format CHROMA-D
Array Size (pixels x pixels)	1280 x 480		2000 x 500	2000 x 2000
FOV (degree)	7.5	7.5	4.87	19.48
Ground Swath (km)	92.42	92.42	60.01	240.1
FOV pixels on FPA	462	770	500	2000

	Instrument 2			
	Current design			future (Flight) design
FPA	baseline FPA (CHROMA_A)	Baseline design, if integrated with 18 micron pixel FPA	Baseline Design, Integrated with small format CHROMA-D	large format CHROMA-D
Array Size (pixels x pixels)	1280 x 480		2000 x 500	2000 x 2000
FOV (degree)	4.6	4.6	3.42	13.70
Ground Swath (km)	56.59	56.59	42.13	168.5
FOV on FPA (pixels)	403	672	500	2000

Radiometric Performance Estimate

Instrument 1
(745 – 772 nm for Oxygen-A band and SIF remote sensing)

	Detector	CHROMA-A		CHROMA-D (A_0 series)	CHROMA-D (A_1 series)
Instrument 1 (745 – 772 nm)	Charge Capacity (k e-)	700	1000	1000	180
	Pixel pitch (µm)	30		18	
	GSD (km)	0.4		0.24	
	Image pixels on FPA	1080 x 462		1800 x 770	
	Signal per pixel (e-)	6757		2435	
	Noise Per Pixel (e-)	126	170	169	62
	SNR per pixel	53	40	14	40
	Total SNR (per 2km x 2km spatial resolution element @ 5% albedo and 65° solar zenith angle)	338	252	152	416

Instrument 1 SNR estimates are based on: spectral radiance at top of the atmosphere 402 $W/m^2/sr/um$, albedo 5%, solar zenith angle 65°, FOV 7.5° per S and P polarization, ground swath 92.4 km, F/2.11, aperture 25 mm, slit width 60 um, total optical transmission 0.71, integration time 0.148 s.

Radiometric Performance Estimate

Instrument 2
(1595 – 1659 nm for CO2 and CH4 remote sensing)

Instrument 2 (1598 – 1659 nm)	Detector	CHROMA-A		CHROMA-D (A_0 series)	CHROMA-D (A_1 series)
	Charge Capacity (k e-)	700	1000	1000	180
	Pixel pitch (μm)	30		18	
	GSD (km)	0.28		0.168	
	Image pixels on FPA	813 x 403		1375 x 670	
	Signal per pixel (e-)	8523		3070	
	Noise Per Pixel (e-)	133	175	171	67
	SNR per pixel	64	49	18	46
	Total SNR (per 2km x 2km spatial resolution element @ 5% albedo and 65° solar zenith angle)	482	368	225	580

Instrument 2 SNR estimates are based on: spectral radiance at top of the atmosphere 60.2 W/m^2/sr/um, albedo 5%, solar zenith angle 65^o, FOV 4.6^o per S and P polarization, ground swath 56.6 km, F/1.89, aperture 40 mm, slit width 60 um, total optical transmission 0.71, integration time 0.148 s.

Summary and Conclusion

- CARBO is a tech demo instrument, funded by NASA's IIP program
- We have designed Instruments 1 and 2 of the CARBO instrument suite to be implemented with the CHROMA-A at JPL, and the design can be integrated with CHROMA-D
- The current ground swath is 92 km for Instrument 1 and 56 km for instrument 2, driven by our CHROMA-A array size. For a large format CHOROMA-D (2k x 2k pixels) the ground swath can be increased to 240 km and 168 km, respectively.
- CARBO takes advantage of the large array formats of FPAs
  - More spectral coverage
  - More spatial coverage
  - Allows for simultaneous imaging of both polarizations

Summary and Conclusion

- These instruments advance the following key technologies:
  - Immersion gratings
  - Simultaneous polarization sensing
    - Dual polarization sensing has both science and engineering benefits.
  - New generation of large format FPAs
  - Modular architecture for a common instrument bus
- These new instruments will greatly enhance the capabilities of existing earth-observing instruments.
- A Flight design would trade mass and size